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The Validity and Reliability of 1-Hz and 5-Hz Global Positioning Systems for Linear, Multidirectional, and Soccer-Specific Activities

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Purpose: The study aimed to analyze the validity and reliability of commercially available nondifferential Global Positioning System (NdGPS) devices for measures of total distance during linear, multidirectional and soccer-specific motion at 1-Hz and 5-Hz sampling frequencies. ***Methods:*** Linear (32 trials), multidirectional (192 trials) and soccer-specific courses (40 trials) were created to test the validity (mean ± 90% confidence intervals), reliability (mean ± 90% confidence intervals) and bias (mean ± 90% confidence intervals) of the NdGPS devices against measured distance. Standard error of the estimate established validity, reliability was determined using typical error and percentage bias was established. ***Results:*** The 1-Hz and 5-Hz data ranged from 1.3% ± 0.76 to 3.1% ± 1.37 for validity and 2.03% ± 1.31 to 5.31% ± 1.2 for reliability for measures of linear and soccer-specific motion. For multidirectional activity, data ranged from 1.8% ± 0.8 to 6.88% ± 2.99 for validity and from 3.08% ± 1.34 to 7.71% ± 1.65 for reliability. The 1-Hz underestimated some complex courses by up to 11%. ***Conclusions:*** 1-Hz and 5-Hz NdGPS could be used to quantify distance in soccer and similar field-based team sports. Both 1-Hz and 5-Hz have a threshold beyond which reliability is compromised. 1-Hz also underestimates distance and is less valid in more complex courses.

Keywords: motion analysis, soccer, team sports, GPS

Recent developments in Global Positioning System (GPS) technology have provided the means to overcome the logistical issues and restrictions of other time-motion analysis methods to quantify athlete locomotion. Portable systems that allow simultaneous real-time data collection on multiple athletes are particularly suited to team sports such as soccer where motion patterns are typically random

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and intermittent in nature[1] and include bouts of intermittent high-intensity and sprint activity.[2]

The accuracy of 1-Hz GPS technology during linear human locomotion has previously been quantified using both differential (dGPS)[3] and nondifferential (NdGPS)[4] systems. These studies concluded that both GPS methods were valid for the assessment of speed, but only in specific environmental conditions such as open sky[3,4] and on relatively linear courses.[5] Townshend et al[6] and Barbero-Alvarez et al[7] reported acceptable validity for 1-Hz NdGPS for the assessment of both speed and position during human locomotion over set courses, and various studies have established good validity of distance measured on bespoke courses by 1-Hz NdGPS during team sport simulated motion activity.[8–10] Previous researchers did, however, conclude that the error of 1-Hz NdGPS systems increased when high velocity and/or multidirectional motion was introduced.[8] Consequently, manufacturers developed NdGPS systems that sample at 5-Hz; a development which should intuitively improve both validity and reliability of data. Recently, Petersen et al[11] measured the reliability and validity of cricket-specific activity using 5-Hz NdGPS systems. Although they reported these systems were reliable and valid for estimating distances over 600 m they showed an underestimation of shorter sprint activity with typical error between 3-40% and, as with 1-Hz GPS, decreased reliability as velocity increased.[11]

The increasing use of 1-Hz and 5-Hz NdGPS in soccer and other field based team sports warrants further investigation into the validity and reliability of this technology before scientists and practitioners can confidently use it to inform practice. To date no previous research has assessed the application of NdGPS technology to specific locomotion patterns which characterize elite soccer performance. Consequently, the aim of this study was to investigate the validity and reliability of commercially available NdGPS devices during linear, multidirectional and soccer-specific motion using both 1-Hz and 5-Hz sampling frequencies.

Methods

To ensure consistency of transit around each course one male participant was used throughout all trials. The participant was healthy and regularly involved in frequent recreational sport activity. Informed consent was obtained from the participant, and ethical approval was gained from the local Institutional Review Board.

Commercially available 5-Hz NdGPS devices (MinimaxX Version 2.5 (Firmware 6.52), Catapult Innovations, Canberra, Australia; weight 67 g, dimensions 50 mm × 18 mm × 88 mm) were used. Devices were worn between the shoulder-blades in custom-made vests, supplied by the manufacturer. The length of each course was established before each set of trials using a validated, calibrated trundle wheel (MeterMan, Winnebago, Minnesota, USA). The linear and multidirectional courses were completed at two speeds (walking mean 1.79 $m{\cdot}s^{-1}$; running mean 3.58 $m{\cdot}s^{-1}$). The participant wore headphones linked to an MP3 player that relayed audio beeps at 1-s intervals to control pace. Markers were placed 1.79 m and 3.58 m apart along the length of each course for walking and running trials respectively. By passing successive markers on each audio beep the required velocity was maintained and the course was completed within the set time. The participant was familiarized with this method before trials being conducted. All trials were completed on the same full-sized artificial FieldTurf surface.

Linear Course. The sideline of the soccer pitch, from the corner-flag to the half-way line, was used (Figure 1a). For each trial, the participant began with the GPS device directly over the start point, and commenced movement when directed by the audio cue. After a brief acceleration phase, a steady velocity was achieved and maintained in time with the audio beeps before stopping sharply with the GPS device directly over the finish point. The participant remained stationary for 30 s between each trial in order to demarcate the GPS data. Sixteen trials were performed at both movement velocities.

Multidirectional Courses. Multidirectional movements were assessed using a series of six mapped courses based on existing line-markings on the soccer pitch (Figure 1a, 1b, and 1c). Sixteen trials were performed on each course at each velocity with eight trials being completed in both directions. The same pacing strategy was used as for the linear trials.

Soccer-Specific Courses. Ten English Premier League soccer matches were analyzed (ProZone Stadium Manager version 3.4) to determine typical movement characteristics for three playing positions (central defender, central midfielder, and forward). These characteristics were converted relative to match exposure ($m \cdot min^{-1}$). One English Premier League game was subsequently analyzed and a 1-min segment of the game was selected that best represented the movement characteristics for each playing position (Figure 2). A 1-min bout of high-intensity (HIB) activity, characterized by greater amounts of high-intensity activity and accelerations, than the typical 1-min efforts was also selected (Figure 2). Each one-minute segment was analyzed for angle of turn, turn frequency, velocity of movement, and change in velocity. Movement maps were subsequently extracted from the software and recreated in the field. A goniometer was used to accurately determine turn angle, the trundle wheel was used to determine distance between turns, and cones and verbal cues were used to control changes in movement direction and velocity. The participant then performed ten trials for each 1-min bout of activity, with full recovery allowed between trials. Table 1 provides further course details for linear, multidirectional and soccer-specific trials.

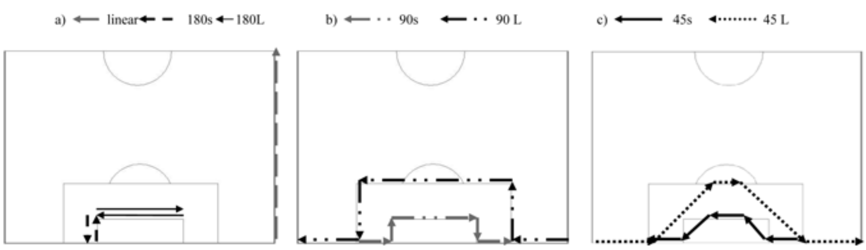

Figure 1 — Motion maps for linear and multidirectional trials.

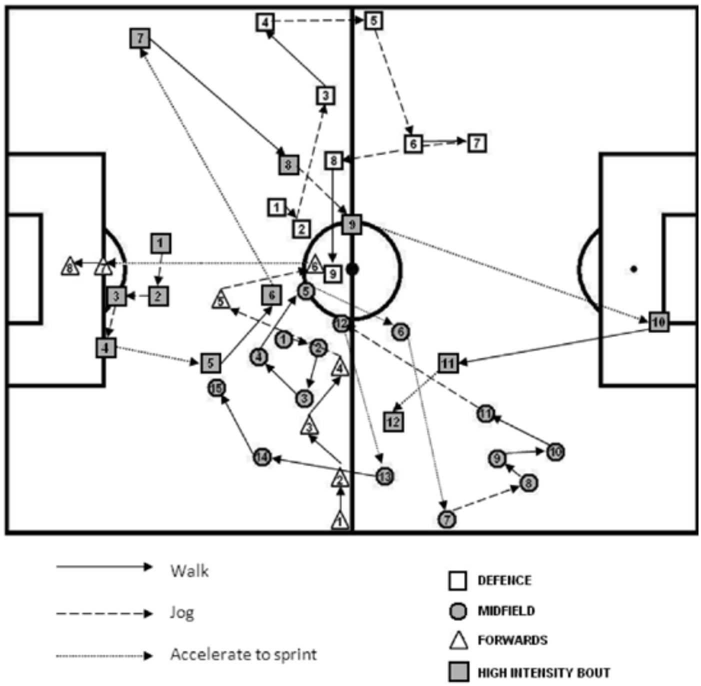

Figure 2 — Motion maps for soccer-specific trials.

Table 1 Course details for linear, multidirectional and soccer-specific trials

Course	Length (m)	Number of Turns	Acceleration to Sprint	Mean Velocity ($m{\cdot}s^{-1}$)	Peak Velocity ($m{\cdot}s^{-1}$)
Linear	51	N/A	0	1.79 and 3.58	—
180 small	55	9	0	1.79 and 3.58	—
180 large	180	9	0	1.79 and 3.58	—
90 small	51	4	0	1.79 and 3.58	—
90 large	99	4	0	1.79 and 3.58	—
45 small	37.5	4	0	1.79 and 3.58	—
45 large	76	4	0	1.79 and 3.58	—
SS D	121	7	0	2.0	5.0
SS M	134	13	3	2.3	7.3
SS F	110	5	1	1.8	7.0
SS HIB	197	9	4	3.3	8.2

Posttrial analysis for all trials was conducted using proprietary software (LoganPlus version 4.2.3), from which distance covered for 5-Hz and 1-Hz sample frequency mode was determined. Validity, reliability and bias were established using a similar method to Petersen et al[11] and were aligned with previous recommendations.[12] Confidence intervals (90% CI) gave the precision of the estimate[13] for each statistic. Comparisons between measured distance and GPS distance (1-Hz and 5-Hz) were drawn using Pearson product moment coefficients (r). Validity of distance measures was assessed by comparing the NdGPS reported distances to the trundle wheel measured distance (criterion). Standard deviation of the mean percentage error of NdGPS derived distance from the measured distance provided the standard error of the estimate (SEE). Typical error (TE) was reported using the percentage coefficient of variation (CV) and was used to characterize the reliability of the NdGPS derived distance data. Bias was calculated by subtracting criterion distance from GPS derived distance and then dividing this score by the criterion distance. The effect size (ES) statistic was generated to demonstrate the magnitude of the mean difference between the measured and NdGPS distance. The criteria for interpreting effect size statistic was: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, and >2.0 = very large.[14] The effect of GPS type and playing position on bias was examined statistically using a two-way analysis of variance (ANOVA) on log transformed data. Significance was accepted at $P < .05$. Finally, a smallest worthwhile change (SWC) was established to consider the smallest change of practical importance and was calculated as 0.2 multiplied by the between subject standard deviation.[15] If the TE was < SWC the GPS device was capable of identifying a SWC and is classed as "good" and, if the TE was = SWC the GPS device was capable of identifying a SWC and is classed as "ok." If the TE was > SWC the devices are rated as marginal."[15]

Results

For all completed trials, number of locked satellites ranged from 4 to 9 (mean = 7) providing adequate coverage while horizontal dilution of precision (HDOP) displayed a mean of 1.5. Before measuring the trial courses the trundle wheel was compared with tape measured distance over a 2 m course on 10 occasions and provided a mean distance of 2 m ± 0 with a Pearson correlation of $r = 1.0$.

Validity

For all the courses and distances used within our study the Pearson correlation for the relationship with measured distance was $r = .99$ for 1-Hz NdGPS and $r = .99$ for 5-Hz NdGPS. This data displayed a weak amount of heteroscedasticity ($R^2 = .16$), thus indicating that as measurement values increased there were only small measurement differences.

Agreement between NdGPS distance and measured distance was variable depending on trial conditions including course complexity and movement velocity (Table 2). Both sample frequencies demonstrated comparable SEE values for validity in linear motion during walking and running activity (2.6 to 2.7% for 1-Hz and 2.9 to 3.1% for 5-Hz). For multidirectional motion, 5-Hz NdGPS

Table 2 Standard error of the estimate of 1-Hz and 5-Hz NdGPS for linear, multidirectional and soccer-specific motion (percent standard error of the mean ± 90% confidence intervals)

	1-Hz		5-Hz	
	Walk	Run	Walk	Run
Linear	2.7 (1.2)	2.6 (1.15)	3.1 (1.37)	2.9 (1.27)
Multidirectional				
180 S	3.8 (1.67)	6.8 (2.99)	3.2 (1.38)	3.6 (1.58)
180 L	3.0 (1.32)	3.4 (1.49)	4.4 (1.9)	3.1 (1.35)
90 S	2.9 (1.29)	3.5 (1.52)	2.2 (0.98)	3.6 (1.59)
90 L	1.8 (0.8)	2.4 (1.04)	2.5 (1.10)	2.2 (0.98)
45 S	4.2 (1.86)	3.6 (1.59)	3.1 (1.34)	2.2 (0.97)
45 L	2.7 (1.19)	4.0 (1.76)	2.2 (0.97)	2.3 (1.03)
Soccer-Specific				
	1-Hz	5-Hz		
DFN	3.0 (1.72)	2.2 (1.27)		
MID	2.8 (1.62)	1.5 (0.89)		
FWD	1.3 (0.76)	1.5 (0.9)		
HIB	2.2 (1.27)	1.5 (0.85)		

demonstrated validity ranging from 2.2 to 4.4% for SEE. However, with the increasing complexity of the course, particularly during running activity there was a trend for the error to increase. The 1-Hz NdGPS (SEE 1.8 to 6.8%) showed a larger range of error compared with 5-Hz. 1-Hz was comparable to 5-Hz for the less complex courses but for the small 180° running course the error was greater for 1-Hz NdGPS. In the soccer-specific trials, the SEE in both 1-Hz and 5-Hz was similar and ranged from 1.3 to 3% for 1-Hz and 1.5 to 2.2% for 5-Hz.

Reliability

For linear motion reliability was comparable for both 1-Hz and 5-Hz NdGPS and TE ranged from 4.4 to 4.5% for 1-Hz and 4.6 to 5.3% for 5-Hz (Table 3). For multidirectional trials a reduction in reliability corresponded with an increase in course complexity. For 1-Hz NdGPS TE ranged from 3.1 to 7.7% and 5-Hz NdGPS had a slightly smaller range for TE of 3.4 to 6.1%. During the soccer-specific trials TE in both 1-Hz and 5-Hz were comparable, ranging from 2.0 to 4.9% for 1-Hz and 2.2 to 4.5% for 5-Hz.

Table 3 Reliability of 1-Hz and 5-Hz NdGPS for linear, multidirectional and soccer-specific motion (coefficient of variation with 90 confidence intervals)

	1-Hz		5-Hz	
	Walk	Run	Walk	Run
Linear	4.38 (0.98)	4.54 (0.99)	5.31 (1.2)	4.55 (1.01)
Multidirectional				
180 S	4.73 (1.11)	7.71 (1.65)	4.79 (1.18)	6.11 (1.45)
180 L	5.65 (4.42)	5.21 (3.94)	6.72 (5.39)	5.33 (4.16)
90 S	5.21 (1.16)	5.86 (1.27)	4.34 (0.96)	5.93 (1.32)
90 L	3.08 (1.34)	4.13 (1.79)	4.12 (1.79)	4.02 (1.76)
45 S	5.70 (0.90)	5.07 (0.81)	5.56 (0.89)	3.78 (0.61)
45 L	3.87 (1.27)	5.85 (1.92)	3.42 (1.13)	3.71 (1.24)
Soccer-specific				
	1-Hz	5-Hz		
DFN	4.86 (3.34)	4.49 (3.09)		
MID	4.56 (3.60)	2.82 (2.25)		
FWD	2.03 (1.31)	2.21 (1.40)		
HIB	4.10 (4.62)	3.32 (3.80)		

Bias

For the walking linear motion both 1-Hz and 5-Hz NdGPS overestimated criterion distance by less than 1% (ES trivial). For the higher intensity running motion 1-Hz underestimated by about 2%, (ES small) and 5-Hz underestimated by approximately 1% (ES trivial). For multidirectional motion, with the exception of the 90° large course where distance was overestimated within 1% the 1-Hz NdGPS underestimated distance from 1% (ES trivial) to 11% (ES large) (Figure 3). For 5-Hz differences from criterion ranged from 2% overestimation (ES small) to 3% underestimation (ES small). Differences for 5-Hz NdGPS across all trials were considered trivial or small (Figure 3). During soccer specific activity both sample frequencies differed from criterion measures by between 1% underestimation and 1% overestimation (ES trivial to small). No significant differences were observed between 1-Hz and 5-Hz for sampling frequency (P = .227); playing position (P = .445); or position × sampling frequency (P = .805). The SWC across all trial types was 0.6% for 1-Hz and 0.2% for 5-Hz. TE for both sample frequencies across all trial types were substantially greater than the SWC (2.2–6.8%) and therefore NdGPS was classed as "marginal" for identifying small changes of practical importance.

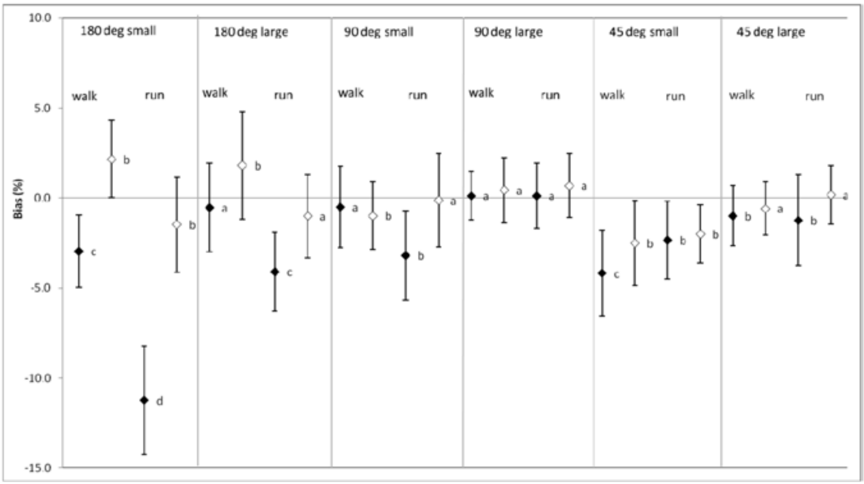

Figure 3 — Percent bias (±90% confidence intervals) and effect size of the mean difference between measured distance and GPS derived distance for multidirection motion. [a]Trivial, [b]small, [c]moderate, [d]large and [e]very large magnitudes of difference between trundle wheel measured distance and GPS measured distance.

Discussion

This study aimed to investigate the validity and reliability of 1-Hz and 5-Hz NdGPS derived data for measurement of distance covered during linear, multidirectional and soccer-specific motion. Our findings demonstrate NdGPS to be a valid and accurate tool for field-based assessment of distance covered during linear and soccer specific motion when a 5% threshold is adopted as in recent previous work.[8,9,11] These results are consistent with those reported in previous studies using 1-Hz NdGPS technology in various simulated team-sport situations.[8–10] This study builds on previous work by demonstrating that 5-Hz NdGPS provides comparable validity results to 1-Hz NdGPS. For multidirectional motion, NdGPS at 1-Hz and 5-Hz was valid for all courses, with the exception for the 1-Hz data on the 180° small course. The 1-Hz mode underestimated data by moderate to large differences (approx. 4–11%) on 45° and 180° courses. The 5-Hz was more accurate and only differed by trivial or small amounts (approx. 0–2%) for all courses. These findings are consistent with recent work by Duffield et al[16] who reported that GPS underestimates distance in confined spaces but that 5-Hz was more accurate at higher speeds in small spaces than 1-Hz.

For all trials, regardless of sampling frequency, NdGPS units were unable to detect small but practically important changes due to TE being substantially higher than the SWC. Manufacturers should strive to address this issue to improve reliability further. However, reliability of the linear and soccer-specific trials for 1-Hz and 5-Hz was within 5% and therefore met the criteria set out in recent similar studies[8,9,17]. For the multidirectional trials we concur with the findings of Petersen et al[11] in that a threshold is reached with multidirectional motion where, at both sampling frequencies the technology may become less reliable. In our study this occurred when turn angle increased to 180° and TE increased to 7.7% for 1 Hz and 6.1% for 5-Hz. Reliability values were marginally better at the running velocity for 5-Hz throughout all trials. Across all trials typical error of the 1-Hz and 5-Hz NdGPS ranged from approx. 2–8%. This is consistent with previous findings for low to moderate intensity activity.[8,10,11] However, our data included activity with intense turn frequencies and repeat sprint activity within the soccer-specific and multidirectional trials. We report better reliability for such data than was previously reported[8,11] where typical error for such activity was approx. 30–37%.

The reliability and bias of our data, especially from the soccer-specific trials, are therefore in conflict somewhat with recently presented data.[8,11] Petersen et al[11] suggested that cricket-specific sprint activity is underestimated by up to 37%, and that NdGPS is currently unreliable for measurement of sprint activity. The technology used by Petersen et al[11] is similar to that used by us; however, markedly different protocols were used to collect data. In addition, the nature of high intensity and sprint activity used in cricket is different to that for soccer. In cricket high intensity activity is usually more linear in nature and the overall intensity levels are lower.[11] Furthermore, in Australasia, where previous data was collected,[8,11] a local satellite has been used as an intermediary between other satellites and the receiver units, but in Europe there is no such intermediary. This fundamental difference in the way receiver units interface with satellites may have contributed to differences in results reported between the studies. It is unclear as to what version of firmware and software Petersen et al[11] and other previous authors[8] used. Manufacturer upgrades of either may also be a factor in the reported differences between studies. It could also be possible that the GPS constellation is denser over Europe, providing better coverage for GPS signals.

It could be that some of the error identified in the data we report between measured distance and NdGPS distance was due to the actual motion path taken during the NdGPS trials differing slightly from the originally measured distance.[8] Nevertheless, data derived from both NdGPS sampling frequencies, particularly at 1-Hz, showed decreasing reliability with increasing course complexity. It would be rare in competitive soccer games and other field-based team sports for athletes to consistently run and turn repeatedly at angles of 180° or 90°.[2,18] Such trials were, however, included in this study to test the limits of performance of the NdGPS technology. At times however, such shuttle run activities may be employed in team sport training environments, and we thus suggest caution be taken when interpreting GPS data in these circumstances. For training activities of lower intensity on courses where turn angle and frequency are less demanding, for example, like those used by Barbero-Alvarez et al,[7] both 1-Hz and 5-Hz NdGPS could be used.

Previous advice has identified that GPS technology operates most effectively in open spaces to enable connection with sufficient satellites.[4,5] Therefore, in agreement with Osgnach et al[19] we would suggest that NdGPS technology could be used in professional soccer in open space training environments to better enumerate load and specificity of training and also for analysis of reserve team and youth team fixtures played in such settings. Practitioners should be cautious when comparing results of training data collected with NdGPS to different match analysis systems that may be used to collect game data in stadia.[20] It should be noted that manufacturers of the GPS devices used in the present study may use unique algorithms to determine GPS distance,[10] making it probable that the results of this investigation relate solely to the brand used.[11] For the soccer-specific trials we used 1 min of simulated activity repeated across forty trials. Therefore, not all activity performed by soccer players within a game (eg, jumping, sliding and ball contact) was included. However, motion was measured from stationary through to sprinting speed and this provides a substantial validation of the technology in this context, although the study did not include workload based on the raw speed-time relationship. Analysis of the validity of motion characteristics used in activities such as small-sided games, on playing areas smaller than that used during competitive match-play were beyond the scope of this study. However, such activities are regularly used in training for soccer and other field-based team sports and so the capacity of this technology to measure motion accurately within such activities should be addressed in the future.

Practical Applications

Both 1-Hz and 5-Hz NdGPS showed acceptable validity and reliability and could be used to measure total distance motion in soccer and similar field-based team-sport environments. Both methods produced valid and reliable measures of linear motion and could be used to precisely quantify total distance motion in linear sport activity such as running. For multidirectional motion, both 1-Hz and 5-Hz were valid and reliable in less challenging scenarios but not in the more complex where reliability decreased, notably during repeated 180° turn angles. On such courses 1-Hz validity and accuracy may also be questionable. For all trials it should be noted that presently NdGPS is incapable of detecting small but practically important changes (SWC). However, NdGPS devices can be used to quantify match-play distance in soccer and other similar team games. We recommend they are used in open spaces, to quantify total distance motion in competitive game and training environments.

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